Heliocentric Distance of Coronal Mass Ejections at the Time of Energetic Particle Release: Revisiting the Ground Level Enhancement Events of Solar Cycle 23

Using the kinematics of coronal mass ejections (CMEs), onset time of soft X-ray flares, and the finite size of the pre-eruption CME structure, we derive the heliocentric distance at which the energetic particles during the ground level enhancement (GLE) events of Solar Cycle 23. We find that the GLE particles are released when the CMEs reach an average heliocentric distance of ~3.25 solar radii (Rs). From this we infer that the shocks accelerating the particles are located at similar heights. Type II radio burst observations indicate that the CMEs are at much lower distances (average ~1.4 Rs) when the CME-driven shock first forms. The shock seems to travel ~1.8 Rs over a period of ~30 min on the average before releasing the GLE particles. In deriving these results, we made three assumptions that have observational support: (i) the CME lift off occurs from an initial distance of about 1.25 Rs; (ii) the flare onset and CME onset are one and the same because these are two different manifestations of the same eruption; and (iii) the CME has positive acceleration from the onset to the first appearance in the coronagraphic field of view (2.5 to 6 Rs). Observations of coronal cavities in eclipse pictures and in coronagraphic images justify the assumption (i). The close relationship between the flare reconnection magnetic flux and the azimuthal flux of interplanetary magnetic clouds justify assumption (ii), consistent with the standard model (CSHKP) of solar eruption. Coronagraphic observations made close to the solar surface indicate a large positive acceleration of CMEs to a heliocentric distance of ~3 Rs before they start slowing down due to the drag force. The inferred acceleration (~1.5 km/s/s) is consistent with reported values in the literature.